Non-axisymmetric Torsional Oscillations of Relativistic Stars

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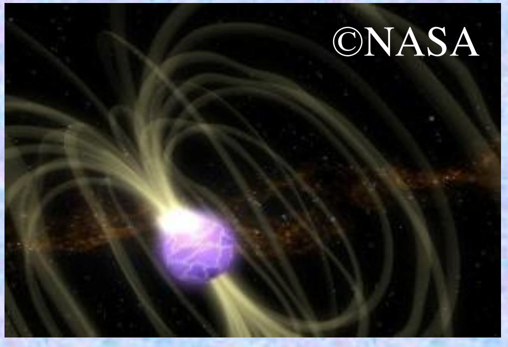
Observations

- Soft gamma Repeaters and Anomalous X-ray Pulsars are candidates of **Magnetars**, which are neutron stars with strong magnetic fields.
- **Soft gamma Repeaters** (SGRs)
  - radiating sporadic X- and gamma-ray bursts (~ 10^{41} erg/s)

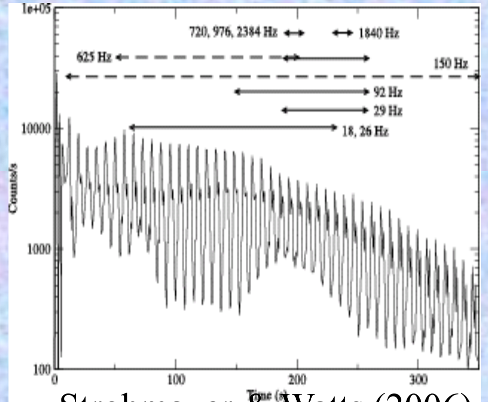


- **Giant Flare from SGRs (10^{44}-10^{46} ergs/s)**
  - SGR 0526–66 in March.5.1979
  - SGR 1900+14 in August.27.1998
  - **SGR 1806–20** in December.27.2004
- In the decaying tail after the flare, QPOs are found !!

→ Barat et.al. (1983); Israel et.al. (2005);
Watts & Strohmayer (2005, 2006)

- SGR 0526-66 : **23ms (43Hz)**, $B \sim 4 \times 10^{14}$G, $L \sim 10^{44}$ ergs/s
- SGR 1900+14 : $B > 4 \times 10^{14}$G, **28, 54, 84, and 155 Hz**
- SGR 1806–20 : $B \sim 8 \times 10^{14}$G, $L \sim 10^{46}$ ergs/s

18, 26, 30, 92.5, 150, 626.5, and 1837 Hz
(also 720Hz ?? and 2384 Hz ??)

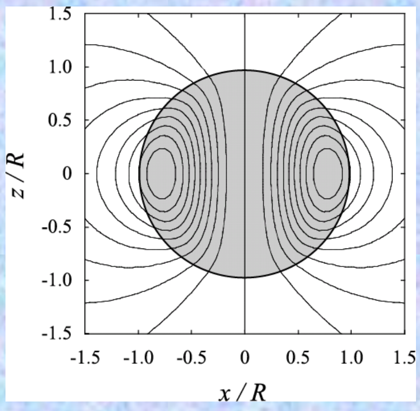


Strohmayer & Watts (2006)

Final goal of our study is to explain these observed evidences theoretically.

Models of Magnetar

- Ideal MHD approximation
  → Electric fields are zero for comoving observer.
- The stellar deformation due to the magnetic fields are neglect.
  - Magnetic energy / gravitational energy ~ 10^{-4} $(B/10^{16}[G])^2$
  - Equilibrium configuration : static spherically symmetric
- Axisymmetric poloidal magnetic fields



Perturbations

- Linearizing the equation of motion and Maxwell equations
  - Cowling approximation ($\delta g_{\mu\nu} = 0$)

How to explain QPOs - I

- **QPOs of SGRs are due to the crust torsional oscillations ??**
  - In Newtonian; Hansen & Cioffi (1980), McDermott et al. (1998), Carroll et al. (1986), Storhmayer (1991), …

→ the case without magnetic fields

$$ {}_\ell t_0 \sim \frac{\sqrt{\ell(\ell+1)\mu/\rho}}{2\pi R} \sim 16\sqrt{\ell(\ell+1)}\ \text{Hz} \qquad {}_\ell t_n \sim \frac{\sqrt{\mu/\rho}}{2\Delta r} \sim 500 \times n\ \text{Hz} $$

→ ${}_2t_0 = 39,\ {}_3t_0 = 55,\ {}_4t_0 = 72,\ {}_5t_0 = 88,\ {}_6t_0 = 104,\ \cdots,\ {}_\ell t_1 = 500,\ \cdots$

  - In GR; Schumaker & Thone (1983), Leins (1994), Samuelsson & Andersson (2006), Sotani, Kokkotas & Stergioulas(2007)

- This attempt might be *partially* successful.
  - The stellar models with stiff EOS and massive star are favored.
  - However, it is found the difficulty to explain all observed frequencies of QPOs.
  - Explanation for lower frequencies could be impossible with only using the crust torsional oscillations.

  → Observed frequencies in SGR 1806-20; 18, 26, and 30Hz

  → *The interval of observed frequencies is much smaller than that expected by the torsional oscillation with different values of l.*

How to explain QPOs - II

- **Alfven oscillations in the core region ??**
  - Levin(2006), Glampedakis et al. (2006)
  - Levin(2007) : the QPO frequencies are enhanced at their edges or turning point.
  - Sotani et al. (2008) : find the two families in Alfven QPOs
  - Colaiuda et al. (2009), Cerda-Duran et al. (2009) : more detailed studies
- Time evolution of two dimensional wave equations
  - Spectrum of Alfven oscillation becomes ***continuum***.
  - There exist two families; ***upper and lower QPOs***.
  - $f_{Ln} \approx 0.6 \times f_{Un}$, $f_{Un} \approx (n+1) \times f_{U0}$, $f_{Ln} \approx (n+1) \times f_{L0}$, $f \propto B$.
- Observed frequencies of QPOs in SGRs
  - SGR 1806-20 : 18, 26, 30, 92.5, 150 Hz

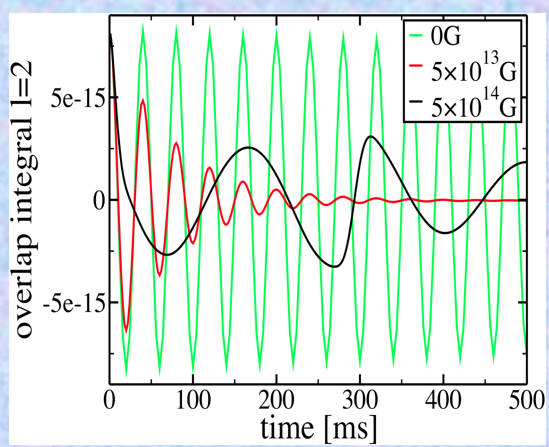
0.6 ×3 ×5

??

– ***Still, it seems to be difficult to explain all observed frequencies.***

Magneto-Elastic Oscillations

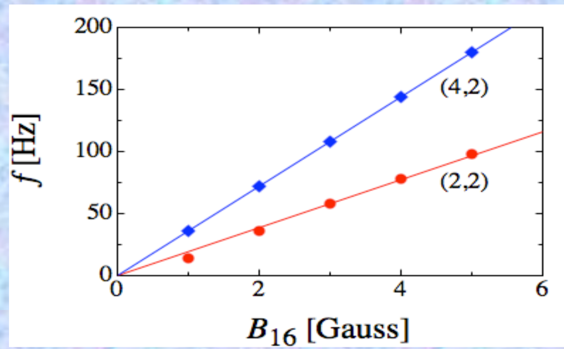
- Gabler et al. (2010) make a numerical simulations of axisymmetric torsional Alfven oscillations in magnetars including the crust region.
  - With weaker magnetic strength, one can observe only the crust oscillation.
  - With stronger magnetic strength, only Alfven oscillations can be observed.
  - The critical magnetic strength for exchanging the oscillation type is $B \approx 4 \times 10^{14}$ G ??
- Thus, the axisymmetric axial type oscillations in the mangetar could become (i) crust oscillations or (ii) Alfven oscillations
  - **One might not observe the both types of oscillation.**
- To explain the observed evidences, alternative types of oscillation should be considered.
  - Polar type oscillations ?
    - Sotani et al. (2009) suggested that the typical frequencies in magnetars are around 100 Hz.
  - **Non-axisymmetric oscillations ?**



Gabler et al. (2010)

Non-axisymmetric Oscillations

- The axial oscillations are coupled with the polar ones even for non-rotating magnetars.
  - As a first step, we consider the only axial type oscillations.
- We find that…
  - **non-axisymmetric axial Alfven oscillations are discrete oscillations.**
    - It could be excited that the both crust and Alfven oscillations ??
  - **Those frequencies are smaller than that of axisymmetric axial type Alfven oscillations.**
    - Axisymmetric case; minimum frequency is around 15 Hz for B=4×10^{15}G
    - Non-axisymmetric case; f_{22}=7.7 and f_{42}=14.4Hz for B=4×10^{15}G
- This type of oscillations could be important to explain theoretically the observed evidence of QPOs in the SGR
  - To fit the possible stellar model with the observations in SGRs, it is necessary to produce more oscillation frequencies with different value of (l,m) for the stellar models constructed with different EOSs.



Conclusion

- QPOs are found in the SGRs.
- As well as crust torsional oscillations, the axial Alfven oscillations might be partially successful to explain the observed frequencies, still those are impossible to explain the all.
- In more realistic stellar model, in which the coupling between the core and crust region will be considered, the axisymmetric torsional oscillations become crust type or Alfven type of oscillations.
  - One needs to consider another type of oscillations.
- Non-axisymmetric, axial type Alfven oscillations becomes discrete spectrum.
- The typical frequencies of this type of oscillations become smaller than those for the axisymmetric torsional oscillations.
- Non-axisymmetric oscillations could be important to explain the observed evidences.

Future works

- Dependence of the toroidal magnetic field on the oscillation frequency ??
- Introducing the effect of crust region.
- Coupling between the axial and polar oscillations.

Thanks for your attentions